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Assessment of Coated Particle Fuels for Space Nuclear Power and Propulsion Systems

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There is a wide variety of fuel variants that could be proposed for space reactor systems, including recapture of historic space reactor fuels, new custom fuels, and modification of terrestrial fuel forms. In this study, terrestrial fuels were surveyed and assessed for use in fission surface power (FSP), nuclear electric propulsion (NEP), and nuclear thermal propulsion (NTP) systems. Fuel forms being developed for advanced reactor designs, including TRISO coated particle fuels, were found to be capable of operating under similar conditions to space power reactors (FSP and NEP) but require modification to be optimized for space applications. Based upon material limits and development status, the most probable coated particle fuel options were identified for each system (FSP, NTP, and NEP). For each system, the coated particle fuel options were assessed to determine required technology development needs to support fuel qualification and compared to an assessment performed for a reference historic space reactor fuel form developed. Comparison of terrestrial coated particle and historic fuels allowed for relative risk to be assessed and common fuel development needs that are design independent to be identified for each system.

I. BACKGROUND

Space reactors are advantageous for in-space power and propulsion due to their capability for high power density and long operating lifetimes. Since the 1950s, the development of these systems has been pursued within the United States (U.S.) and internationally with the goal to enable capable, robust, and sustainable exploration of our solar system. There are three fundamental applications of space fission power and propulsion currently under consideration by NASA: fission surface power (FSP), nuclear electric propulsion (NEP), and nuclear thermal propulsion (NTP). Reference system performance parameters representative of current NASA missions are shown in Table 1.

TABLE I. Reference System Parameters for Current NASA Space Nuclear (Fission) Applications

	FSP	NEP	NTP
Power	50 kW_{th}	10 MW_{th}	500 MW_{th}
Outlet Temp.	1200 K	1200 K	2700 K
Coolant	Na Heat Pipe	Li or HeXe	H_2
Operating Duration	10 years	5 years	10 hours

There exists an extensive development history of space reactor technologies within the U.S. alone. However, through past U.S. development efforts, none of these technologies have yet been fully demonstrated to meet current performance requirements. Additional technology development is required for each of these systems to ensure the reactor is at an appropriate readiness for NASA missions.

Overall system readiness requires the integrated system, all subsystems, and their components to be demonstrated to meet functional, performance, and safety requirements under operational environments[1-4]. As the subsystem and its underlying components are matured, they must be demonstrated at increasingly representative scale and environments (Fig. 1). For reactors, this includes improving the readiness of manufacture/assembly processes, the material performance databases, and the reactor operations database.

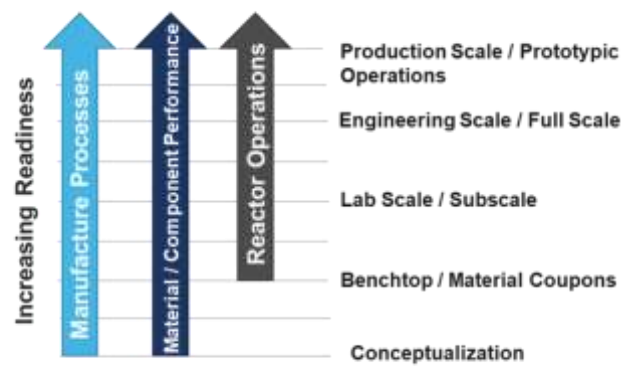

Fig. 1. Readiness considerations for space reactor development

Fuel is a critical component to enable reactor reliability and performance. Fuel selection is a major technical decision made during the system design. Fuel selection plays a large impact on overall system performance as well as technical risk that must be addressed during the development program, which is expected to have a major impact on program cost and schedule. There is a wide variety of possible fuel variants that could be proposed, including fuels developed through past space reactor programs, new novel fuel designs, and existing terrestrial fuels modified for space reactor applications. This study surveyed terrestrial fuel types and identified fuel development needs for space reactor applications. Through this effort, for each system (FSP, NTP, and NEP), coated particle fuel technologies adapted from existing terrestrial fuel programs were evaluated against a reference historic fuel to understand the benefits and disadvantages of leveraging coated particle fuel technologies for space applications.

I.A. Study Process

The study approach was performed in two phases (figure 2). In the first phase, ongoing terrestrial reactor development

efforts were surveyed. The state of the art for coated particle fuel fabrication and existing performance databases were identified through literature review and expert interviews. In this phase, coated particle fuel forms for space reactor applications were identified. The second phase of the study focused on the fuel assessment. For each system, each terrestrial coated particle derivative and one reference fuel form from past space programs were assessed. The assessment included three categories important to fuel development: performance, technical risk, programmatic (cost and schedule). Comparison of terrestrial coated particle fuel and historic fuel derivatives allowed for relative risk to be assessed and common fuel development needs to be identified.

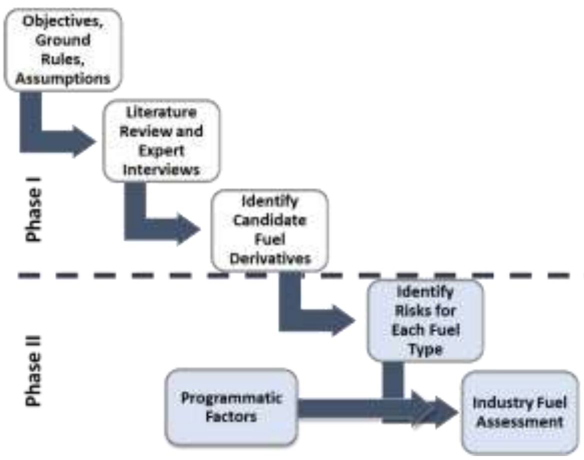

Fig. 2. Assessment process used in this study.

II. TERRESTRIAL FUEL SURVEY

Many U.S. companies are currently working to develop and deploy advanced power reactors based on different technology approaches (e.g., gas cooled, metal cooled, and salt cooled; thermal or fast spectrum). In most cases, each reactor uses a different fuel design which could be grouped with similar types with slight variations in design (Fig. 3). The reactors being developed through current programs[5-14] are based upon the following fuel types: metallic (UZr, or UMo), ceramic (UO_2, UC_x, or UN), TRIstructural-ISOtropic (TRISO), molten salt, and hydride ($UZrH_x$). Each of these fuel types has significant heritage from past programs. Many of these fuels are envisioned to be fabricated using a high assay low enriched uranium (HALEU) feedstock. Ongoing DOE Advanced Reactor Demonstration[5] and Department of Defense (DOD) Pele[6] programs are actively developing tailored versions of metal, oxide, and TRISO fuels; they are expected to develop new production scale fuel fabrication lines to support future reactor demonstration activities.

The surveyed advanced reactor fuel forms will be developed to be capable of operating under similar conditions (operating temperatures, working fluids, lifetime) to space power reactors. Of the solid fuel options being developed, ceramic pellet (UO_2 and UN) and TRISO coated particle fuels correspond to reactor designs with the highest operating temperatures (≥ 600 °C, 873 K) and are the assessed to be the most applicable terrestrial fuel options for high performance

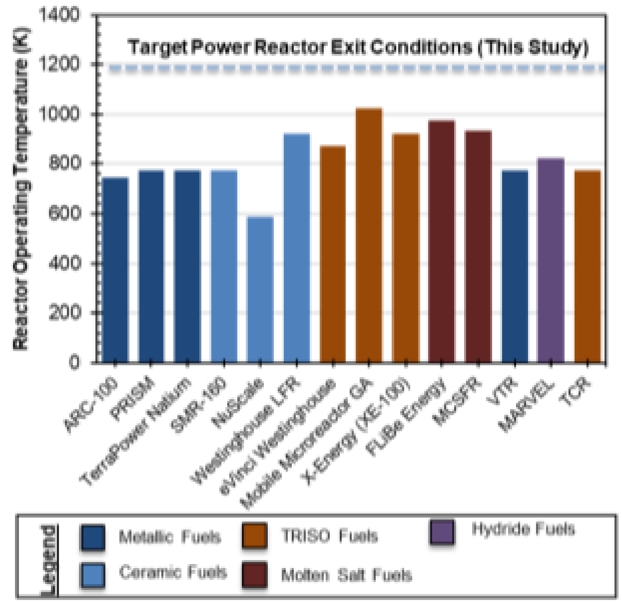

Fig. 3. Comparison of operating conditions and fuel types for some reactor designs under development in the U.S.

space reactors. Metallic (UMo) and hydride ($UZrH_x$) fuels would be alternative fuel candidates for lower operating temperature FSP or NEP systems (fuel temperatures of less than 1075 and 975 K respectively). Each of these fuel types have a high manufacture readiness level and existing performance database that could be leveraged for space applications.

II.A. Fuel Qualification Considerations

Fuel qualification has been defined[15] as "*a process which provides high confidence that physical and chemical behavior of fuel is sufficiently understood so that it can be adequately modeled for both normal and accident conditions, reflecting the role of the fuel design in the overall safety of the [reactor design]. Uncertainties are understood such that any calculated fission product releases include appropriate margin to ensure conservative calculation of radiological dose consequences*". Successful completion of the fuel qualification program establishes the data needed to assure decision makers that reactor operations with a given fuel type will allow system safety and performance requirements to be met. Therefore, the fuel qualification process in many cases has become synonymous with fuel development, whereby the end of fuel qualification indicates a high readiness and confidence in the developed fuel form and corresponding reactor system.

Fuel qualification is design and application specific. Use of a fuel qualified for terrestrial applications in a space reactor does not necessarily ensure the fuel is ready for space reactor operations. The objectives of fuel qualification for advanced reactor development programs are defined in NUREG-2246, "Fuel Qualification for Advanced Reactors" (Ref. 16): (1) demonstrate process to reliably fabricate a fuel product in accordance with a specification, and (2) demonstrate fuel performance and ability to meet reliability needs or licensing

safety-requirements through analysis and testing. Therefore, when assessing the readiness of fuel candidates for space reactor applications, the following questions were considered:

- Can the required fuel design be fabricated? Have all fabrication processes been previously demonstrated and at what scale?
- Has fuel performance been demonstrated for the range of operating conditions required of the space reactor? Does a predictive fuel performance model exist which has been validated by test data?

II.B. Coated Particle Fuel State of the Art

Significant international research has been performed on coated particle fuel development by the United States, Germany, England, Japan, France, Russia, South Africa, the Republic of Korea, and China (Ref. 17-26). Notably, several coated particle variants have been developed and tested in demonstration reactors or prototype plants within the U.S., Germany, China, and England. This historic development has been superseded in recent years with concerted efforts to develop standardized, highly reliable, and higher performing fuel forms. Current coated particle fuel development programs have primarily focused on preparing a specific fuel particle architecture (TRISO) for commercial advanced high temperature reactor applications.

II.B.1. Advanced Gas Reactor TRISO Development

The advanced gas reactor (AGR) program[25] is currently the primary U.S. fuel qualification program for TRISO fuels. Under AGR, the qualification program developed a specific TRISO fuel form variant (Fig. 4), a UCO TRISO particle in a cylindrical graphite matrix pellet compact, for high temperature gas reactor applications. Fuel performance goals under AGR were to demonstrate a coated particle fuel form capable of operation under a peak burnup of 20% fissions per initial metal atoms (FIMA) and temperatures of 1250 °C (1523 K). Demonstrating desired reliability (measured by fission product release fraction) is a key goal for the development of this fuel form in order to demonstrate that the fuel design serves as a fission product containment mechanism. The reference performance goals of the standard AGR fuel design guided the selection of fabrication and testing parameters for all demonstration activities. Therefore, modifications of the TRISO design would not be considered a qualified fuel form as a part of the AGR effort. Since the start of the program in 2002, fuel development has spanned over 20 years and \$367 million total investment is planned to meet program objectives by the program's anticipated end date in 2024 (Ref. 27).

Following the successes of the AGR program, many new reactor applications have been envisioned with substantial efforts dedicated to demonstrating the extensibility of fabrication, modeling and simulation, and testing techniques to AGR TRISO variants[29-32]. While these variants are not qualified and require additional technology development, the existing TRISO fabrication and testing infrastructure has the possibility to be leveraged to reduce cost and schedule for the development of new coated particle fuel forms.

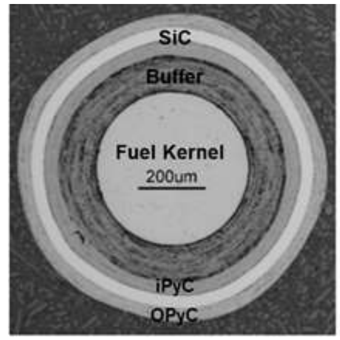

Fig. 4. AGR TRISO cross section (modified from Ref. 17).

II.B.1. Space Reactor Coated Particle Fuel Development

Coated particle fuel development is not limited to terrestrial reactor programs, coated particle fuels have also been developed in past space reactor programs. U.S. NTP development programs[33-36] have focused a significant portion of past fuel development on coated particle-based fuels. Coated particle fuels have also been surveyed for past NEP reactor applications[34,35,37], however development efforts were much more limited. All past programs baselined a HEU enrichment which influenced particle design.

For NTP applications, coated particle-based fuel forms can be largely grouped into three categories: graphite matrix, ceramic metallic (cermet), and particle fuels. Cermet fuels were assessed to be least extensible to current NASA NTP missions due to the fast spectrum design enabled by use of HEU fuel kernels in a W-matrix. Thermal, HALEU reactor variants have been designed, but correspond to lower operating temperatures due to the use of a Mo-W alloy matrix. These fuel types could be made using existing TRISO fabrication infrastructure but would require the most modification. The graphite matrix and particle fuels, developed through the Nuclear Engine for Rocket Vehicle Applications (NERVA)/Rover and space nuclear thermal propulsion (SNTP) programs respectively, were assessed to be more extensible to HALEU reactor applications due the use of a moderated reactor design, but neither of these programs developed fuels to the temperatures required for current NASA NTP missions (up to 2500 K exit temperature demonstrated). Recapturing historic NTP fuel forms would allow for the program to leverage the existing fuel performance database and lessons learned from past fabrication efforts. However, additional technology development would be required to improve fuel performance for higher operating temperatures, power densities, and durations. These fuel types could be made with the existing TRISO fabrication infrastructure with some modification. All in all, because NTP requires high temperature, hydrogen operations (> 2700 K), TRISO fuel forms would require modification and technology development for NTP applications.

For NEP applications, cermet and modified TRISO fuels have been considered to meet the relatively high operating temperature and long lifetime requirements, but limited investment has been pursued in the development of such fuel

forms. Coated particles were identified to be capable of some possible advantages including: restrained fuel swelling compared to pellet designs, prevention fuel and fission product migration, and prevention of fuel-coolant or fuel-cladding/liner interactions. Similar to NTP, due to low uranium density and high parasitic neutron absorption by the cermet metal matrix, larger core sizes may be required. This design was only recommended for fast reactor systems. Existing TRISO designs exhibit a significant overlap in the required performance database for NEP applications, but a drawback of the TRISO design for NEP applications is the very low uranium loading which increases reactor volume and mass. Due to the diverging design requirements for reduced mass NEP reactors compared to terrestrial reactors, modifications to the fuel design were desired to enable higher operating temperatures and power densities.

II.C. Terrestrial Fuel Survey Key Findings

UO_2, UN, and TRISO based designs were the only terrestrial fuel candidates capable of meeting the reference FSP and NEP operating temperatures. Terrestrial fuels require significant modification for NTP applications.

Space power reactor systems have similar operating conditions, but different design drivers than high temperature terrestrial reactors. FSP and NEP designs require a higher uranium loading fuel form to minimize required critical volume to reduce overall reactor and shield mass. Modifications of existing coated particles to increase uranium loading includes: increased particle volume loading, removal of coatings, reduced coating thicknesses, and increasing kernel diameter to increase volume fraction of fuel in the particle. NTP designs require much higher operating temperatures and a fuel form capable of high-power densities (> 5 MW/L) and hydrogen compatibility. Desirable modifications to existing coated particle fuels for NTP applications include: a high melting temperature (> 2850 K) fuel kernel, hydrogen compatible coatings, coatings with low parasitic neutron absorption, and reduced coatings/coating thicknesses to improve uranium loading or effective thermal conductivity.

Based upon material limits and development status, the most probable coated particle fuel options that would be proposed for space applications are:

- **FSP** – AGR TRISO or modified AGR TRISO (increased kernel diameter, reduced coating thicknesses, increased particle loading) within a graphite matrix in a moderated reactor.
- **NEP** – modified TRISO with a large diameter UN kernel, increased particle loading, and modified coating layers within a graphite or SiC matrix in a moderated reactor.
- **NTP** – modified BISO with a UC_x or UN based kernel or modified TRISO with a ZrC coating and UC_x or UN based kernel within a graphite or ZrC matrix in a moderated reactor.

While there exists an industrial base and pre-existing infrastructure for coated particle fuels, modified fuels will require additional technology development and should not be considered already qualified for space reactor use.

Space reactor fuels should not have the same qualification, performance, and safety requirements that are required for terrestrial applications. Terrestrial fuel qualification has primarily focused on minimizing risk and mitigating consequences of fission product release. This philosophy results in fuel qualification being an extensive (and expensive) process spanning many years. Fission product release characteristics are not likely a driver for space reactor applications. Fuel requirements and demonstration activities should be tailored to ensure the mission and reactor performance can be met. This approach could greatly reduce the schedule and cost for space reactor fuel qualification.

III. FUEL ASSESSMENT

For each system, a modified terrestrial coated particle and reference fuel types from past programs were assessed for space reactor applications (Table II). These fuels were evaluated for three categories important to fuel development:

- **Performance Range and Existing Performance Database:** SME qualitative assessment of the ability of the design to meet or exceed reference system parameters and comparison of required fuel operating conditions to the existing performance database.
- **Technology Gap Assessment:** identification of technology gaps based upon gaps in the existing fuel performance database and technology development needs specific to the reference reactor system.
- **Cost and Schedule:** projected cost and schedule investment for fuel development before a reactor demonstration (TRL 6).

TABLE II. Fuel Forms Considered in this Assessment

	FSP	NEP	NTP
Coated Particle Fuel Derivative	AGR TRISO in Graphite	Modified TRISO in Graphite	Modified Coated Particle in Graphite or ZrC
Historic Fuel Derivative	UO_2 Pellet (Ref. 38)	UN Pellet (Ref. 39)	UC_2-Graphite Matrix (Ref. 33)

III.A. FSP Fuel Assessment

Due to higher uranium loadings, reactors will be smaller (lower volume and mass) with UO_2 fuels compared to TRISO fueled reactors. Fast and thermal reactors possible with HALEU UO_2 fuel systems. Moderated-UO_2 reactors would yield the lowest mass. With the AGR TRISO, epithermal and thermal HALEU reactors would be possible. Modification of the AGR TRISO would improve performance but increase development schedule. There exists an extensive fuel performance database for UO_2 fuel forms from its use in commercial light water reactors and development from past space reactor programs. This database fully spans the required FSP fuel performance parameters. Similarly, the AGR irradiation database exists for relevant temperature range and burnups. Modification of the AGR TRISO design for higher uranium loadings would require new test data to be generated.

Existing test data does exist for some AGR TRISO variants and existing fuel performance models could be used for predictive analyses and design.

FSP fuel types were assessed to be easier to mature (low relative cost and schedule) to the readiness desired to enable a reactor subsystem demonstration (Table III). This is primarily due to the ability to leverage ongoing terrestrial development activities for FSP reactor development. This advantage offers two primary benefits for FSP fuel development: ability to leverage existing fuel performance database and fabrication processes for terrestrial modified fuel forms, as well as the ability to leverage existing facilities infrastructure for testing and demonstration activities. This allows for reduced overall testing program scope, cost, and schedule. HALEU FSP reactor designs can benefit from moderation to minimize critical mass. If moderation is used, moderator development will be a key technology development challenge. If a high readiness fuel form (UO_2, UN, unmodified AGR TRISO) is selected, moderator development may drive cost and schedule.

TABLE III. FSP Fuel Assessment Results

	UO_2 Pellet	**AGR TRISO in Graphite**
Performance	Fast and thermal reactors possible with HALEU	Moderated TRISO reactors may yield competitive mass
Existing Performance Database	Fully established separate effects test data	AGR irradiation database exists for relevant temperature range and burnups
Technology Gap Assessment	4 Technology Gaps Identified	6 Technology Gaps Identified
Cost	**Low**	**Low**
Schedule	**Low**	**Moderate**

III.B. NEP Fuel Assessment

For NEP reactor designs, the primary design driver is specific mass. Due to high uranium density and high operating temperature capability, UN was assessed as an ideal fuel candidate to reduce required critical mass. Fast and thermal reactors are possible with HALEU UN. Moderated-UN reactors would yield the lowest mass. The modified TRISO was assessed to require moderation to minimize reactor mass but was not expected to be capable of achieving the same mass as UN. Due to significant development under the SP-100 program, there exists an extensive fuel performance database for UN fuel forms for NEP application. This database fully spans the required fuel parameters for NEP. There exists some test data for the modified TRISO (some particle irradiation experiments). More testing is needed to generate modified TRISO fuel performance information for NEP applications.

NEP fuel forms also were assessed to share synergies with power reactors and pellet fuel forms have a large performance database generated through historic programs that could be leveraged in design activities (Table IV). Confirmatory testing of fuels with component designs representative of modern NEP reactor designs and under the bounding representative conditions is still recommended. Performance was assessed to be a higher priority design driver for NEP systems than FSP systems. This results in the desire to develop fuel forms capable of higher operating temperatures and power densities. Because of this, more risks were identified for NEP fuel forms compared to FSP fuels which were anticipated to increase NEP fuel development cost and schedule.

TABLE IV. NEP Fuel Assessment Results

	UN Pellet	**Modified TRISO in Graphite**
Performance	Fast and thermal reactors possible with HALEU	Epithermal and thermal reactors possible with HALEU
Existing Performance Database	Fully established separate effects testing data	Limited test data exists (particle irradiation experiments)
Technology Gap Assessment	7 Technology Gaps Identified	8 Technology Gaps Identified
Cost	**Moderate**	**Moderate**
Schedule	**Moderate**	**Moderate**

III.C. NTP Fuel Assessment

The reference performance parameters of this study are beyond what has been demonstrated through past U.S. NTP programs. For the NERVA/Rover derivative fuel form, operation above 2700 K would require the fuel kernel (UC_2) to exceed its melting point. The reference cercer system had significant uncertainty in its performance potential. While the fuel form design leverages high melting temperature and hydrogen compatible materials, cercer fuel performance limits are not understood due to lack of a pre-existing performance database. Operation up to the theoretical melting temperature of UN (~3100 K) could be possible if the ZrC matrix and coated particle coatings are capable of providing the conditions to prevent UN dissociation or containing UN dissociation products. There is a well-established existing fuel performance database for the NERVA/Rover fuel form. This database includes a fully established separate effects testing (irradiation, hydrogen corrosion, other high temperature tests) database up to 2500 K as well as prototypic performance data from NTP reactor ground tests. Testing to higher irradiation temperatures ($\geq$ 2850 K) would be necessary to demonstrate the fuel is capable of meeting reference system parameters. A fuel performance database is not established for cercer fuels, some fuel and surrogate test data exists of laboratory fuel samples under hot hydrogen testing.

NTP fuel forms were assessed to require the highest cost investment and more technical risks were identified for these fuel types than power systems as shown in (Table V). This assessment was primarily driven by the lack of existing test

data and established fabrication processes for fuel forms under conditions required to meet study performance parameters as well as the low fabrication technology maturity for fuel forms well optimized for HALEU NTP applications. Existing fuel performance database gaps are primarily related to high temperature (> 2500 K) fuel performance under hot hydrogen and combined effects conditions (nuclear and non-nuclear environment). NTP requires operating conditions much exceeding operating temperatures and nuclear environments (power density / flux) than terrestrial fuel forms and a unique working fluid. Therefore, additional investment for new facilities to support combined effects and reactor operations is recommended. These facilities are expected to be cost and schedule driving for NTP fuel development.

TABLE V. NTP Fuel Assessment Results

	Rover / NERVA Graphite Matrix	**Cercer with Modified Coated Particle**
Performance	Operation above 2700 K requires molten kernel operation	Operating temperatures up to 3100 K proposed (UN theoretical T_M)
Existing Performance Database	Fully established separate effects testing data up to 2500 K	Limited test data exists (some fuel and surrogate testing)
Technology Gap Assessment	9 Technology Gaps Identified	11 Technology Gaps Identified
Cost	**High**	**High**
Schedule	**Moderate**	**Moderate**

III.D. Future Space Reactor Fuel Production and Qualification Needs

Fuel qualification activities and related infrastructure were assessed based on the readiness of the fuel form and identified technology gaps. It was found that fuel qualification can be structured into three phases which span initial fuel technology development to reactor operations:

Phase I would include all initial fuel technology development including screening of fuel form types and fabrication technologies. Based on test data, fuel design and fabrication optimization can begin. Existing government or industry laboratory scale fabrication and testing equipment capable of testing fuel under separate effects conditions would be needed during this phase.

Phase II includes all activities until the completion of component level development. During phase II, fabrication processes are demonstrated to produce and assemble full scale fuel assemblies or assembly bundles. Demonstration tests are performed on these fuel components and integrated fuel assemblies (includes non-fuel components such as moderator) to test fuel under near-prototypic conditions (combined effects conditions) which matches or bounds critical parameters which impact fuel performance. For UO_2, UN, and TRISO based fuels, existing production scale equipment could be used to support fabrication activities for this phase. For NTP fuels, a first of a kind "pilot" scale fuel production facility will be needed to fabricate and assemble full scale components. This pilot line could be a government or industry facility. New engineering scale (capable of full-scale component production) equipment will be needed for non-fuel reactor components (such as moderators and insulators).

Phase III corresponds to demonstration of fuel forms under true prototypic conditions via prototypic reactor operations. All fuels will require the dedication of a fabrication process line which will allow for fuel element production at the quality and quantity needed for the demonstration test reactor operations. Power reactors may be tested at existing facilities, modification of facilities may be needed to support MW_e scale NEP reactor operations. NTP reactors will require a new or modified facility for demonstration testing.

IV. CONCLUSIONS

A primary technical challenge of space reactor systems is fuel development . Fuels serve a critical role in the reactor, providing the heat source for power conversion (FSP and NEP) or propellant heat transfer (NTP). Fuel qualification is expected to be a major element of each space reactor development program, which encompasses all fuel fabrication, testing, and analysis activities to mature a space reactor fuel form capable of meeting performance and mission requirements. There is no existing qualified fuel form for any of the space reactors currently of interest to NASA and existing infrastructure dedicated to space reactor fuel development is limited. Ongoing advanced reactor development activities are maturing fuel forms capable of higher operating temperatures and burnups in the range desired for space reactor applications. Additional technology development will be needed to demonstrate fuels are capable of satisfying high system performance parameters, such as those used in this study.

For each system, reference fuel types from past space reactor programs corresponded to a reduced number of technology gaps and a more established performance database. Modified coated particles were assessed to require greater technology development to optimize fabrication processes and develop an existing performance database. Space power reactors can leverage the high readiness, existing infrastructure, and established performance databases of either coated particle or ceramic fuel types from ongoing advanced reactor development programs. NTP can benefit the most from existing coated particle fuel infrastructure as this can be used to fabricate derivatives of historic fuels or new custom fuels. Since NTP fuels would require significant modification of existing coated particle fuel types, more investment in technology development and fabrication infrastructure modifications would be need for fuel development.

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